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Healthy, affordable and climate-friendly diets in India

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ABSTRACT

India has among the highest lost years of life from micronutrient deficiencies. We investigate what dietary shifts would eliminate protein, iron, zinc and Vitamin A deficiencies within households' food budgets and whether these shifts would be compatible with mitigating climate change. This analysis uses the National Sample Survey (2011–12) of consumption expenditure to calculate calorie, protein and the above micronutrient intake deficiencies and relate them to diets, income and location. We show that more than two-thirds of Indians consume insufficient micronutrients, particularly iron and Vitamin A, and to a lesser extent zinc. A greater proportion of urban households than rural households are deficient at all income levels and for all nutrients, with few exceptions. Deficiencies reduce with increasing income. Using constrained optimization, we find that households could overcome these nutrient deficiencies within their food budgets by diversifying their diets, particularly towards coarse cereals, pulses, and leafy vegetables, and away from rice. These dietary changes could reduce India's agricultural greenhouse gas (GHG) emissions by up to 25%. Current agricultural and food pricing policies may disincentivize these dietary shifts, particularly among the poor.

India has the largest number of undernourished children in the world (Saxena, 2008), and among the highest disability-adjusted lost years of life from micronutrient deficiencies – or deficiency of essential vitamins and minerals (Muthayya et al., 2013). Changes in the mix of cereals, which provide over half of Indians' calories, have contributed to a decline in overall nutritional quality (Defries et al., 2015). Despite having the second lowest meat consumption in the world (FAOSTAT), livestock production contributes 10 percent of India's greenhouse gas (GHG) emissions, largely from dairy products. With growing meat consumption in fast-growing urban areas, Indian diets may fast become a global climate concern. The cost, nutritional, and climate impacts of these dietary trends are as yet unknown. This study contributes to the intersection of these three gaps in food and climate research: the lack of attention to micronutrition; the absence of studies of climate mitigation in developing countries with largely vegetarian diets; and the general lack of attention to affordability of dietary shifts that address both nutrition and climate mitigation. With a focus on India, we ask: would eliminating protein, iron, zinc and Vitamin A deficiencies be affordable at current prices and compatible with mitigating climate change, or are there trade-offs among these objectives? What kinds of dietary shifts would further these objectives, while respecting existing dietary patterns? We examine hypothetical scenarios of dietary shifts that satisfy these objectives and draw conclusions for policy on what foods can affordably eradicate micronutrition without exacerbating climate change.

1. Background

India has the 22nd highest Global Hunger Index (GHI) out of 118 countries. About 22.9% of women and 20.2% of men have a below-normal body mass index (BMI) (Ministry of Health and Family Welfare, 2016). Between 1980 and 2005, average calorie intake and protein consumption declined, even while fat consumption increased. However, calorie consumption is not tightly linked to nutrition or health status (Deaton and Dreze, 2009). Although the prevalence of undernourishment (lack of sufficient calories) has decreased to about 15% of the population (Food and Agriculture Organization of the United Nations, 2015), micronutrient deficiencies are far higher and less visible than calorie intake. The largest concentration of people with micronutrient deficiencies live in low income South Asian countries, including India (Mark et al., 2016). Micronutrients are also critical for disease control among children (Caulfield et al., 2006). A recent survey

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of micronutrient intake in select states of India in 2011–12 shows that the proportion of pre-school children who did not meet at least 50% of the Indian Required Daily Allowance (RDA) for calcium, vitamin A, riboflavin and vitamin C ranged from 51 to 82%, while the corresponding figures for adolescents were 52–85% (National Nutrition Monitoring Bureau, 2012). The intake of micronutrients such as iron, vitamin A, riboflavin, vitamin C and folic acid were less than 50% of RDA in 51–83% of pregnant women. More than 50% of women and children are anemic (Ministry of Health and Family Welfare, 2016). Although intake deficiencies do not alone determine adverse health outcomes, they contribute to them.

These surveys on micronutrient intake are conducted only in rural areas. The status of micronutrient deficiencies in urban India is not well understood, though lifestyle changes are causing an increase in obesity and related diseases (Ebrahim et al., 2010; Wang et al., 2009). Globally, urban malnutrition has been long ignored but has gained prominence with increasing urban inequality (Bloem and de Pee, 2017). From outcome indicators measured in one survey, men in urban areas were found to have a lower body-mass index (BMI), but women higher BMI, than their rural counterparts. Urban households in India consume less calories and less cereals than rural counterparts (Shetty, 2002). However, other than broad trends, the relationship between locational dietary patterns, income and micronutrient deficiencies has not been studied.

The increase in high-yielding, low nutrient-content cereals at the expense of more nutritious indigenous varieties of cereals over the last fifty years has reduced the nutritional content of the cereal supply (Defries et al., 2015), which is the mainstay of Indian diets. With the advent of the Green Revolution in the sixties, the government promoted high-yield varieties of wheat and rice, leading to a reduction of 40% in the land on which (the more nutritious) coarse cereals were grown. Coarse cereals (which include different varieties of millets, maize and sorghum) contributed about 17% of the national food basket in 2011–12, but they are consumed largely where they are grown (Directorate of Millets Development, 2014). Policy efforts to improve food security in India, such as subsidies in the Public Distribution System (PDS), have faced challenges in utilization and targeting, and encouraged the consumption of fine cereals (such as polished white rice and wheat) over coarse cereals (Khera, 2011). With the 2013 National Food Security Act, the government intends to promote coarse cereals in the PDS (Department of Food and Public Nutrition, 2017), but efforts are in their infancy.

In the current market environment, the trade-off between nutrition and cost in shifting towards different cereals has not been examined. Other avenues to diversifying diets include shifting to meat, which are typically richer in micronutrients and more bioavailable than vegetarian sources (de Pee and Bloem, 2009). Most Indians have predominantly vegetarian diets, though only a third of Indians are vegetarian on principle (Devi et al., 2014), while the rest presumably are so to save money. India has the lowest per capita meat consumption in the world after Bangladesh (FAOSTAT), though meat consumption in India has been increasing with urbanization and globalization. However, animal sources of protein in general are far more expensive than vegetarian sources, and Indians already spend, on average, over 40% of their household expenditure on food (Anand et al., 2016). As we show later in this paper, among the poorest, this share can be over 90%. What is the most cost-effective way to improve Indians' diets? This question has seldom been asked with respect to micronutrient deficiencies, or with respect to nutrition in general.

Globally, changing diets are having an impact on both health and the environment, including climate change (Tilman and Clark, 2014). While vegetarian sources of protein aren't as rich in micro-nutrients as animal sources, most have lower greenhouse gas emissions intensities (González et al., 2011), with the exception of rice. Global livestock production contributes up to 18% of GHG emissions (Stehfest et al., 2009). In India, greenhouse gas emissions (GHG) from ruminant livestock (cows, goats and lamb) comprised 47% of agricultural emissions, which in turn contribute 20% of India's total GHG emissions in 2014 of ~3 Gtons CO_2eq (Food and Agriculture Organization of the United Nations, 2015). Food consumption trends have not as yet been linked to GHG trends in India. However, given the scale of dietary changes required to eradicate micronutrient deficiencies in India, the question of climate impacts from dietary shifts is pertinent.

In the broader literature, there are some insights to be gained on the compatibility between healthy diets and climate mitigation, though these studies are largely in developed countries, and do not typically consider affordability. A recent systematic review of the literature on sustainable diets (Jones et al., 2016) indicates that 83 of the 114 studies reviewed examined different environmental impacts, of which GHG impacts were the most common component measured. In contrast, only three studies examined as their primary aim the economic costs to consumers of different diets. We identified only three studies that examined any micronutrients as part of nutrition quality, two in France (Masset et al., 2014, Vieux et al., 2013) and one in the Netherlands (Temme et al., 2013). Notably, nearly all studies addressed diets in high-income countries.

The substantive findings in high income countries regarding the compatibility between healthy and climate-friendly diets are mixed, but generally find co-benefits between reduced GHG emissions and improved nutritional quality from reducing total calorie intake and eating less meat (Creutzig et al., 2016). Few studies examine both the cost and environmental implications of healthy diets. In Europe, plant-based food may be healthier and cheaper and have low environmental impact (Tukker et al., 2011, Westhoek et al., 2014). Perignon et al. (2016) show that in France moderate GHG reductions are possible with nutritional adequacy without compromising cost or requiring major dietary shifts. However, these findings don't carry over to other regions, such as India, where diets are still largely vegetarian and undernourishment is a relatively greater threat than obesity, though they increasingly co-exist.

We first provide new insights on the distribution of calorie, protein and micronutrient deficiencies by location, income, and regional dietary patterns. Iron, vitamin A and zinc deficiencies are among the most widespread micronutrient deficiencies in the world (Muthayya et al., 2013). We then examine, using optimization analysis, the synergies and trade-offs in these three related objectives: eradicating undernourishment and micronutrient deficiencies; reducing the cost of improving diets; and minimizing the climate impacts of diet improvements, all while respecting people's current dietary patterns. That is, would eliminating micronutrient deficiencies be affordable at current prices and compatible with mitigating climate change? What dietary shifts would enable such 'triple win' outcomes, if any? With regard to climate mitigation, we examine agricultural emissions, which comprise methane, and nitrous oxides for fertilizers, but excludes energy-related CO_2.

2. Methods

We first characterize patterns of dietary intake deficiencies (DiD) across India, relating them to region (state), urban/rural, and income level. States, or groups of states, roughly identify regional dietary patterns (e.g., wheat-based in the north vs rice-based in the south). Urban/rural reflect differences in access to markets, processed and packaged foods, and globalization, while income groups reflect different budgetary constraints. There are several other important household characteristics that also influence dietary choices, such as religion, education, and others. We do not explicitly analyze these factors, and leave their investigation for future work.

For all these population groups, we calculate the average deficiencies in dietary intake ("deficiency gap") and deficiency counts (i.e., the share of people with a deficiency) based on the Indian RDA, which accounts for the bioavailability of micronutrients in foods and for

habitual Indian diets (Indian Council of Medical Research, 2009).

In the second component, we assess the compatibility between affordability and climate impacts in improving diets to eliminate micronutrient deficiencies. Our goal is to provide insights for food and climate policy on the trade-offs and synergies between these goals, and on the foods that these policies ought to focus. We use an optimization algorithm (See Appendix B for mathematical formulation), because it is structurally suited to assess the compatibility between different objectives subject to nutritional and other constraints. We investigate what diet choices minimize either emissions or cost, while constraining the choice set to those that meet nutritional requirements within households' food budgets. We restrict the flexibility of dietary changes to respect current dietary patterns, culture and habits. Perignon et al. (2016) conduct a very similar optimization analysis for France, but they formulate the objective in terms of minimizing dietary shifts and examine the resulting GHG reductions. We include this formulation in our sensitivities.

For all scenarios, we require that households consume the higher of their present total calories or the minimum calorie requirement for each person, assuming an average of moderate and sedentary activity, and that all micronutrient requirements are met. In our reference scenario ("*Reference*"), we minimize emissions while keeping costs within households' present food budgets. Our default dietary constraints in the *Reference* scenario include: (a) holding constant the calorie shares of different food groups (Fruit/Vegetable (FV), Starch source ((SS-C)), Protein sources (PRTN, non-meat), Meat/Fish (MF), Milk product (MP), and Other (OTH); (b) restricting the extent of shifts away from food items currently consumed within groups (upper bound of a 100 fold increase and a lower bound of 10% of survey levels); and (c) perpetuating characteristics of the Public Distribution System (PDS), such that households continue to buy the proportion of non-PDS cereals as they do in the survey. The importance of constraint (b) is that it indirectly restricts choices to available foods in each region, since those that aren't consumed (close to zero consumption) would not be selected in substantial amounts. Furthermore, we omit minor grain items that comprise less than 1% of total calories from grains. We include two cost sensitivity scenarios, in one of which we assume all rice/wheat are purchased at PDS prices ('ideal' PDS) ('*Ref + PDS*'), and in the other that households can substitute between meat and vegetable protein sources ('*Ref + FlexDiet*'). Animal protein tends to have higher bioavailability than vegetarian protein sources. Since we require that diets meet the Indian RDA, which is based on vegetarian diets, we may overestimate the substitutive equivalent of animal protein, and therefore also the related GHG emissions. We therefore place a higher burden of proof on the demonstration of compatibility between cost and emissions reduction, which only increases the robustness of our conclusions.

We construct two additional scenarios to test the trade-offs between cost and emissions. In one we maximize emissions reductions without regard to cost (that is, remove the food budget constraint) ('*Ref + NoBudget*'), and in the other we minimize cost instead of emissions, to see whether emissions would increase ('*MinCost*'). Lastly, we include a scenario ('*DevMin*') where we minimize deviations from present diets, as an alternative approach to model adherence to present diets, while staying within food budgets and meeting nutritional requirements. All the scenarios are shown in Table 1.

Since there are thousands of diets in the sample survey that we could optimize, we identify 32 representative diets, for each of the four regions (North, South, East and West), for urban and rural separately, and for four income groups. To define the income groups, we use multiples of the Indian poverty line in 2011–12 (Planning Commission of India, 2014) INR 33 and 47 (~PPP $2 and 2.8) per cap per day in rural and urban respectively), where the multiples are 0.5, 1 and 2 (yielding four income groups each). Thus, for rural areas, the income groups are < $1/day, $1-$2/day, $2-$4/day, and > $4/day. For urban areas, the income groups are < $1.4/day, $1.4-$2.8/day, $2.8-$5.6/day and > $5.6/day. Approximately 50 million people in India earn less than $1/day. We include them as a separate group, because their dietary characteristics are distinct from others in poverty. Since our objective is to redress deficiencies, we calculate the baseline representative diets as the mean levels of food consumption of those households in each cluster that are deficient in any of the four assessed nutrients (protein, iron, zinc, vitamin A).

3. Data

We use the National Sample Survey of Consumption Expenditure in India (NSS Round 68, 2011–12) as the basis for assessing dietary intake. The survey is a nationally representative sample of 101,651 households across India, across all states, and urban and rural areas. The National Nutrition Monitoring Bureau (NNMB) repeat surveys, in contrast, report household level 24-h recall data from 8 states and from rural households only. The NSS dataset provides quantities of 114 food items (See Appendix A) consumed on a 30-day recall basis at household level, including food purchased and produced, and a host of household characteristics, related to location, demography, and total expenditure (which we use as a proxy for income). The key motivation of using this dataset is that it allows one to relate diets to other household characteristics. Nutrition surveys typically utilize 24-h recall periods, which may provide a more accurate picture of actual food consumed. By quantifying monthly consumption for a nationally representative sample, NSS may provide a better characterization of broad dietary patterns. The drawback is that there is additional noise in the data due to recall error (i.e., high standard deviations), and the 114 items may omit some categories of food consumption, such as during festivals or items not included in the survey. The NSS distinguishes whole and refined wheat, but doesn't distinguish between types of rice. We use the nutritional content of polished rice, which dominates rice consumption. The nutritional content of red and brown rice is lower than that of wheat and millets, so this simplification is unlikely to affect the results of our optimization analysis.

We omit from the analysis households whose food consumed outside the home is more than 20% of their food expenditure, since we don't know the composition of these foods. The omission of these observations does not bias the sample, because the share of households is even across regions, income levels and urban/rural areas. This is interesting in and of itself, and worthy of investigation in future work. We retain households that eat less than 20% of their total expenditure out, and assumed that the food eaten out has the same dietary composition as the rest of their food, since we have no basis for any other assumption. In effect, we scaled the nutrient intake up in proportion to the extent of this expenditure.

We assemble nutrient content data for the 114 food items in NSS from the Indian food composition tables, 2017, developed by the National Institute of Nutrition. The food quantities in the NSS data are intended to represent consumption, but they most likely reflect purchased quantities because respondents are unlikely to be able to recall the quantity of food actually ingested over 30 days. We therefore include adjustment factors for edible portions, from the Bangladesh Food Composition tables (Institute of Nutrition and Food Science, 2013), which has all the relevant food items and is in close enough geographic proximity and culture to be applicable (See Table A.4). To the extent that households specify actual intake, we would underestimate deficiencies, making our estimates conservative.

To account for differences in individual dietary requirements, we calculate different RDAs for male and female, and for adults and children (thus, four groups in total) (See Appendix Table A1). We convert all members to consumption equivalent units (CU) to make them comparable. We use the definition of CU by the NSS, for each of household member type. On the consumption side, since the survey provides only total household consumption, we assume the four member types consume in proportion to their respective consumption

Table 1
Optimization scenarios and constraints. Y/N means the corresponding constraint (rows) is turned on/off for the corresponding scenario (columns). N/A means the constraint is not relevant for that scenario. PDS: Public Distribution System.

	Scenarios Objective: What minimized	Reference Emissions	*Ref + PDS* Emissions	*Ref + NoBudget* Emissions	*Ref + FlexDiet* Emissions	*MinCost* Cost	*DevMin* Deviations from baseline
Constraints	Meet nutritional requirements	Y	Y	Y	Y	Y	Y
	Fix food group calorie shares	Y	Y	Y	Y	Y	N
	Restrict item intake shifts	Y	Y	Y	Y	Y	N/A
	Fix PDS/non-PDS shares	Y	N	Y	Y	Y	Y
	Meet food budget constraint	Y	Y	N	Y	N/A	Y
	Allow meat/veg protein substitution	N	N	N	Y	N	N/A

equivalent units.

We use direct, non-CO_2 emission factors from the agricultural production stage to assess the climate change impact of various crop and livestock products. The emissions from the production stage take 80%–86% of the total global emissions from the food chain (Vermeulen et al., 2012). For livestock, estimates include CH_4 emissions from enteric fermentation, and CH_4 and N_2O from manure management, and from deposition or application on pasture and cropland. The estimates per type of animal product are sourced from Gerber et al. (2013). For vegetarian sources, emissions factors are based on nitrous oxide (N_2O) from fertilizer use, and additionally methane in the case of rice. We omit CO_2 emissions from agricultural inputs and indirect emissions due to land use changes because these inputs are unavailable by crop for India. Since this is a caveat, we focus on those results (pertaining to dietary choices) of our analysis (rice vs other cereals, meat vs vegetarian protein) whose differences in emissions factors are dominated by non-CO_2 emissions.

We use emission factors for N_2O emissions from synthetic fertilizer applications from the Indian Department of Agriculture & Cooperation (2017), combined with crop production data from a mix of Indian sources (Ministry of Agriculture & Farmers Welfare, 2016) where feasible (for some major crops such as rice, wheat, pulses, maize, and millets) and from FAOSTAT for others (Food and Agriculture Organization of the United Nations, 2015). We obtain CH_4 emissions for rice also from FAOSTAT. The resulting emission factors are all calculated on the basis of Indian production emissions. Imports are negligible for most food groups, such as cereals, vegetables and animal sources. For a few food groups where imports are non-trivial, such as pulses, we implicitly assume that imported products do not have significantly different emission factors.

The NSS survey keeps records of the quantity of food that households purchase from the market. On the other hand, the emission factors from the FAO are per unit weight of the farm-level products (e.g. carcass weight for meat, sugar cane for sugar, etc.). Hence, to estimate emissions from household food consumptions, we harmonize these different weight values by adopting extraction rates—ratio between primary and processed commodity—from FAO's food balance sheet (FAO, 2001). These steps yield direct, non-CO_2 emissions per purchased kg of food.

4. Descriptive results - more than half of Indians have micronutrient deficiencies

Overall, the analysis shows that 74 percent of Indians are consuming calorie deficient diets (assuming they have sedentary to moderate activity levels), and 52 percent have diets that are protein-deficient. However, micronutrient deficiencies are more prevalent. Diets of two-thirds of the population are zinc-deficient, 89% are iron deficient and 85% are Vitamin A-deficient. These deficiencies are driven by diet composition, and the nutritional content of key staples, such as rice and wheat.

A large share of the population are on the margin of being deficient. That is, if one considers 90% achievement of the RDA, 56% are calorie-deficient, 35% protein-deficient, 83% iron-deficient, 55% zinc-deficient, and 80 percent Vitamin A-deficient. In the nutrition field, nutrition adequacy is often assessed as a range between 66% and 100% of the RDA. We found that only 12% of the population consume less than this threshold for calories, 6% for protein, 56% for iron, 22% for zinc and 61% for Vitamin A.

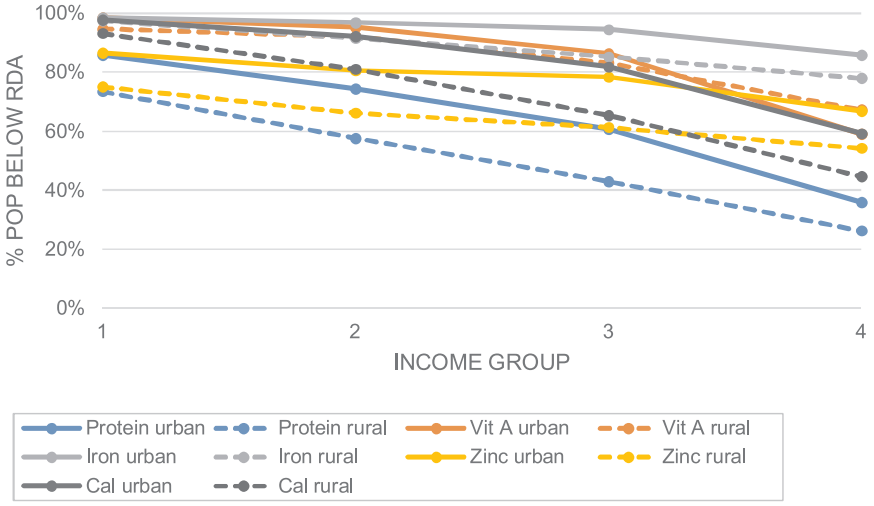

Fig. 1. Micronutrient and protein deficiencies by urban/rural and income group. Share of population in each group with deficiency (with intake lower than the required daily allowances (RDA)).

4.1. Higher income households have lower dietary intake deficiencies

Intake deficiencies decrease with increasing income (Fig. 1). This decrease is most pronounced for total calories, Vitamin A and protein, but noticeably less so for zinc and iron. Two possible reasons that iron and zinc deficiencies scale relatively less with increasing income is that higher income households get more calories from fatty foods, particularly oil, which don't have iron and zinc. Wheat is the primary source of iron for Indians, which is seldom eaten in the South and East. Even in the North and West, where it is the main cereal, wheat provides only about half of total calories.

Virtually all the poorest households are deficient in iron and Vitamin A, and more than 70% have one or more of these deficiencies. In contrast, less than 70% of wealthy rural households are Vitamin A deficient, and less than 30% have a protein deficiency.

4.2. Rural households have lower nutrient deficiencies than urban households

Urban households consistently have higher DiDs than their rural counterparts at all income levels, with the exception of Vitamin A, where with increasing income the difference reduces, and eventually flips, such that fewer urban households in the highest income group are deficient than their rural counterparts (Fig. 2). This exception is driven by diets in the Southern and Western regions (Fig. 3). Here, households consume far less dark leafy vegetables, which is the primary provider of Vitamin A in India. As such, a large percentage are deficient, but urban wealthy households tend to consume more than their rural counterparts of other Vitamin A-rich foods, such as milk, mangoes, carrots or tomatoes. The extent of these deficiencies in each group correlate with the number that are deficient in each dimension (Fig. 2). Thus, rural households of all income groups have (statistically significant) higher average consumption of calories, iron, zinc and protein. We found that the differences in calorie consumption are in some cases up to 15% higher. Rural households in the lowest two income groups have (statistically significant) higher average Vitamin A consumption, but the reverse is true for the two highest income groups.

Rural households have greater diversity in their diets than their urban counterparts. In order to test this, we calculated the Shannon Diversity Index for cereal consumption among all regions and income groups (See Appendix A for details). We found that in almost the entire North and West, rural diets indeed have higher diversity in cereal consumption. In the South, and particularly in the East, urban cereal consumption is slightly more diverse (see Table A.3 for the diversity indices), namely because the rural poor rely more on cheap rice.

4.3. South and east eat less nutritious food than the North and west

Fig. 3 shows the variation in DiDs by state. In general, southern states have the highest DiDs of all micronutrients, eastern regions are among the most deficient in iron and zinc but less so in Vitamin A, while the north and north-western states tend to have relatively lower DiDs (see Appendix, Table A2 for state assignments to regions). The northern and western states have lower protein deficiencies than the southern and eastern states. These variations are attributable in part to regional cereal preferences. The north and west have predominantly wheat-based diets, while the east and south have predominantly rice-based diets. Wheat has significantly more protein and iron than polished rice. In general, the greater (lower) the share of rice (wheat) in total calories, the higher (lower) DiD, which is most pronounced for iron (Fig. 4). In the south and east, even the higher income groups suffer high DiDs. Furthermore, these differences are exacerbated by the fact that cereals comprise a larger share of total calories in the east and south, particularly among the poor. Thus, cereal (and mainly rice's) share among poor households in eastern India is up to 85% of total calories, and as low as 48% among wealthy households in Western India, who eat a combination of wheat and millets (See Appendix, Table A5 for all food group calorie shares).

There are some regional peculiarities. Higher income households in some northern and northeastern states such as Arunachal Pradesh, Mizoram and Jammu and Kashmir have adequate dietary intake of vitamin A, in part because they eat more leafy greens and milk than most other Indians. Milk and spinach provide over 60 percent, and up to 85%, of households' Vitamin A intake.

We now turn to a scenario exercise to determine, based on present dietary patterns and food expenditures, what shifts in diet can eradicate micronutrient deficiencies and how these dietary shifts will affect food budgets and GHG emissions.

5. Healthy diets, their costs and climate impacts

Numerous dietary changes can meet the micronutrient dietary requirements, but change may come at a cost, require changes of habit, or go against current trends associated with rising affluence and globalization. Here we examine hypothetical scenarios of dietary shifts and their impacts in order to provide insights for food and climate policy.

5.1. Food characteristics – nutrition, cost and emissions

Before presenting the scenarios and results, we discuss some of the key characteristics of foods that influence the choice of scenarios. We first show food nutritional content, prices and GHG emissions in general, and then compare food items against these three properties.

5.1.1. Nutritional content of foods

The nutritional content of all 114 food items are shown in Appendix Table A4. Fig. 5 shows the nutritional content (per kg of food) for the 30 largest contributors for each nutrient in the form of a color spectrum (towards red, nutritional content is higher, towards blue, lower). Hence, foods towards the red in the spectrum are the more feasible sources of that nutrient. Notably, rice is less nutritious than wheat (including refined flour), with respect to protein, iron and zinc content, while millets such as pearl millet (local name bajra) are more nutritious than wheat. Zinc tends to be high in protein sources, such as meat, milk and pulses.

5.1.2. Food prices

Average food prices for NSS food items were inferred from total expenditure and quantity consumed. Prices vary significantly across the country, between urban and rural areas, and even within particular locations (Fig. 6). Markets serving higher income urban areas have the highest prices. Food subsidies for rice and wheat under the PDS are not intended to, and do not necessarily, cover all household consumption. Many households purchase a significant share of their rice/wheat on the open market. As a result, the effective price paid for rice and wheat varies widely across the country, by up to a factor of two, even among the poor. Since cereal consumption comprises around 50% of total calories, the access to the PDS has a significant bearing on food budgets and households' choice of staple. For instance, bajra is competitive with rice and wheat on the open market, where available, but is more expensive than their subsidized counterparts. Notably, PDS rice as reported in NSS is cheaper than PDS wheat, although stated government prices are the other way around, but in the open market rice is more expensive. Regarding protein sources, meats and milk are more expensive than lentils per gram of nutrient.

5.1.3. GHG emissions

In general, the most emissions-intensive foods are those that cause methane emissions, which are from ruminant animals (beef and lamb) and rice production. In comparison, the relative differences in emissions intensity across other foods is far smaller. The resulting emissions factors are shown in Appendix Table A4. In comparison to developed

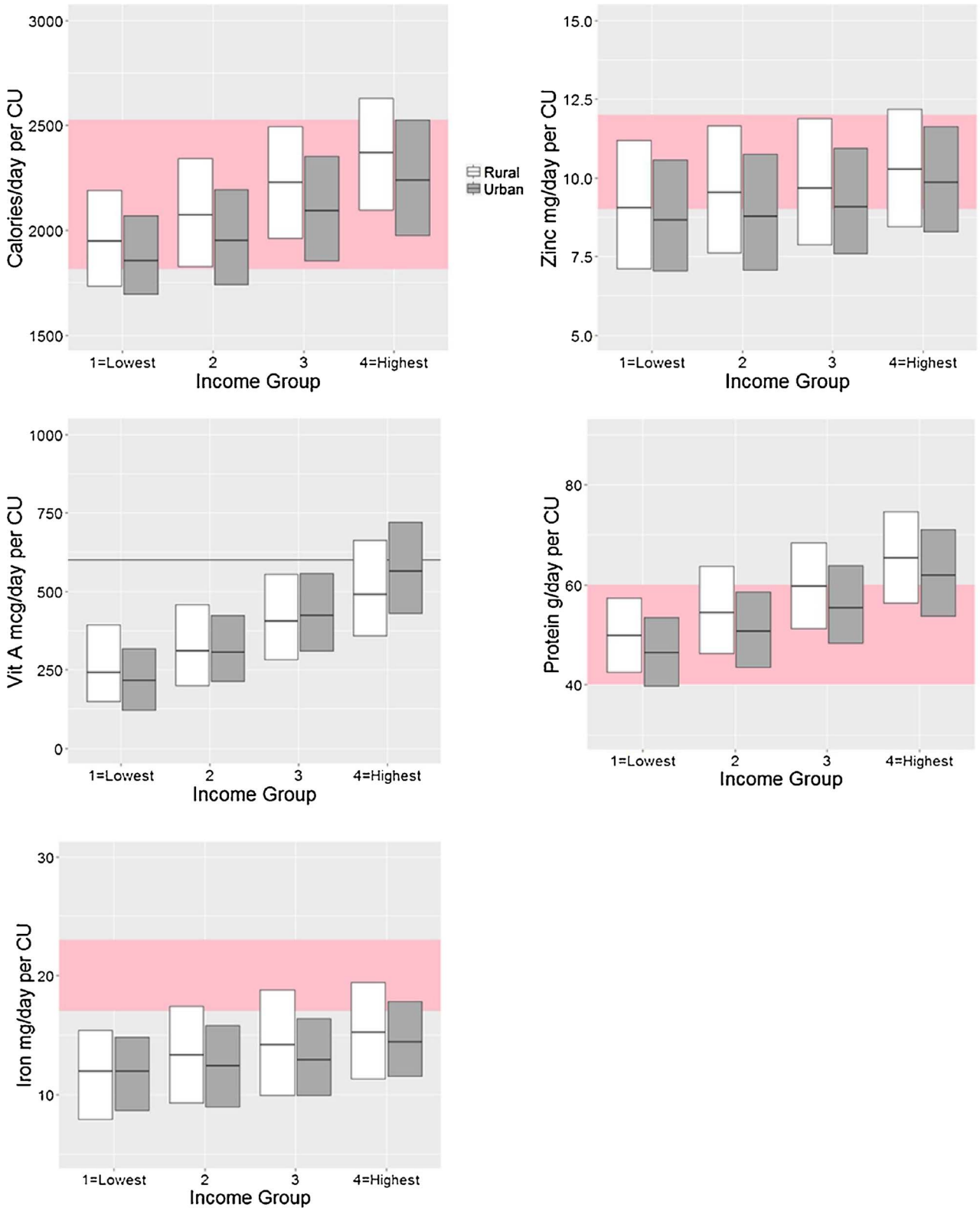

Fig. 2. Average micronutrient consumption by urban/rural and income group compared to RDA (shown in pink, range for children to adult). Data: National Sample Survey of Consumption Expenditure, 2011–2012. Boxes show 75/25 percentiles. Differences in urban/rural average consumption levels by income group are all statistically significant (*t*-tests for the hypothesis that they are the same are all rejected with p-values < 0.001) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

countries, both rice and livestock in India have substantially different emissions intensities. Emissions from beef production in India are over a factor of three of that in Western Europe and over double that of in the United States, because of low feed digestibility, poorer animal husbandry and lower carcass weights, among other factors (Gerber et al., 2013). Methane emissions from rice production in India, on the other hand, varies widely due to different cropping patterns and flooding times (Vetter et al., 2017), but on average tend to be on the

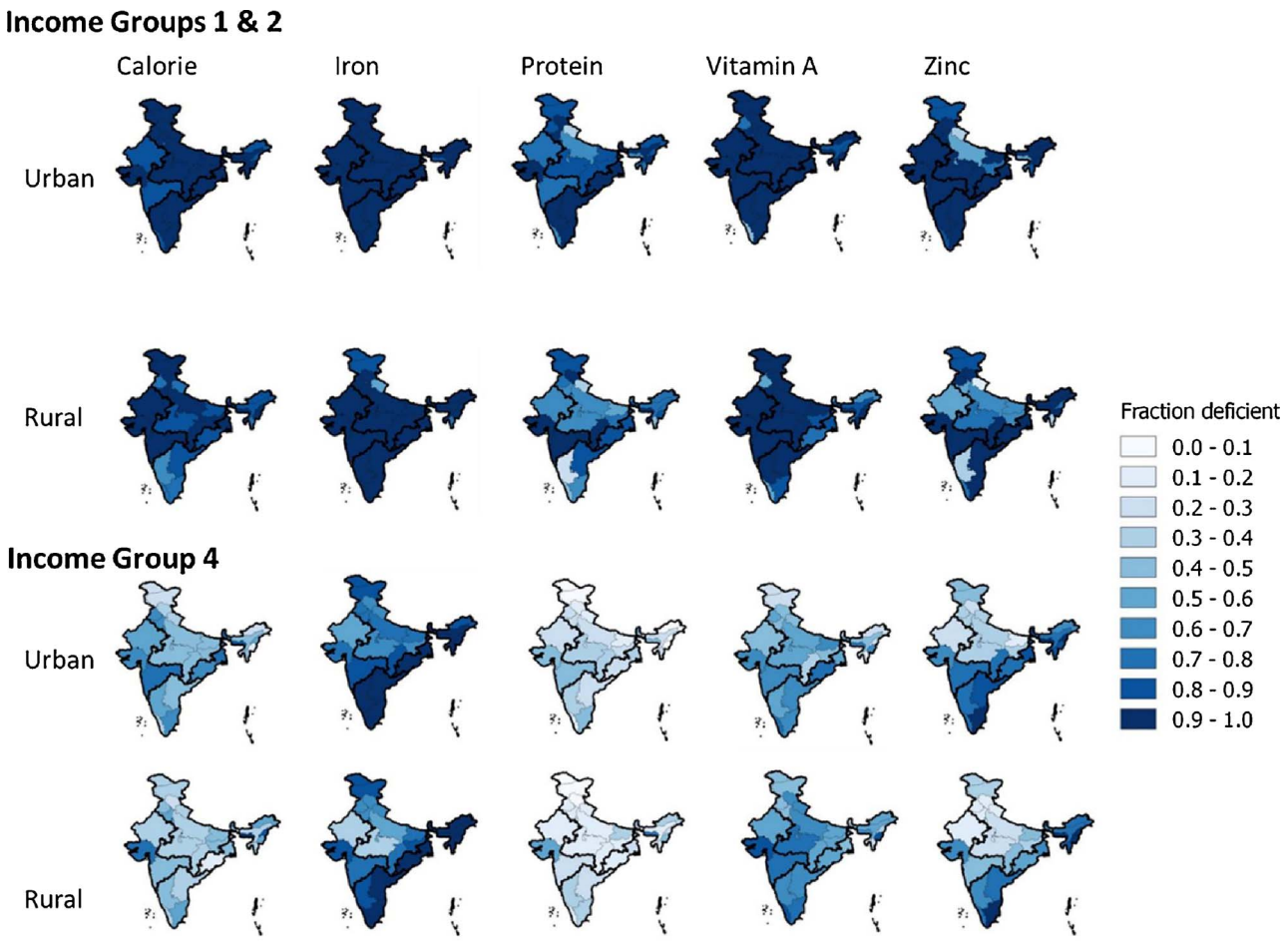

Fig. 3. State-wise macronutrient and micronutrient deficiencies by income and urban/rural. Income groups 1–4 thresholds defined as multiples 0.5, 1 and 2 of Indian poverty line of (~PPP $2 and 2.8) for rural and urban areas respectively. Data source: NSS 68, 2011–2012. Bold lines show regions (North, South, East, West).

lower side compared with those of other rice-growing regions in the world (Yan et al., 2003). Besides the presence of these emissions intensive foods, the emissions footprints of diets depend primarily on total calorie consumption, which in turn scales with income. Thus, per capita food emission footprints increase with income, but at similar incomes, are comparable (Appendix Table A5). At high income levels, in most cases urban footprints tend to be slightly higher than rural ones. At the lowest income level, in many regions rural household have higher footprints, due mainly to higher rice consumption.

5.1.4. Food comparisons – cost and emissions per nutrient

Fig. 5 shows the cost and emissions per nutrient for all four nutrients for the top 30 items in terms of nutritional content of the applicable nutrient. Food items towards the lower left of each chart are preferred from an affordability and climate perspective, since they have the lowest cost and emissions per nutrient respectively. The group of foods comprising these preferred foods represent preferred diets based on these two criteria, conditional on food budget and other constraints. Thus, bajra is a preferred grain, because it is on the bottom left of the graphs for all nutrients but for Vitamin A. Bajra is currently eaten only in a few states in Northern and Western India. Khesari, a pulse eaten by the poor in North India but banned until recently due to a toxin causing neurological disorders, would be the preferred protein source. Carrots and dark leafy vegetables are the preferred sources of Vitamin A. Overall, diets with the bulk of calories met by wheat and bajra, pulses, and dark leafy vegetables would provide sufficient nutrients with the least cost and climate impacts. However, when factoring in different cultural patterns and food budget constraints, the more realistic dietary shifts likely vary by region and income level, and are more diversified, as discussed below.

5.2. Optimization results

5.2.1. Win-win-win for health, affordability and climate mitigation possible

Our main result from the *Reference* scenario is that households above the poverty line can meet their nutritional requirements within their present food budgets (Fig. 7). However, many households below the poverty line (in the two lowest income groups), comprising the bottom 160 million, would have to exceed their food budget to attain nutritional adequacy (for these groups, their corresponding cost and emissions would be those associated with the *MinCost* scenario). These households face an increase in their food budgets (which are, on average, 59% of total expenditure) of about five percent. Notably, these improved diets come with a benefit to climate - they lead to a 19% reduction in food-related GHG emissions, or 122 million tonnes out of 632 m tonnes (FAOSTAT). This result is even stronger if households can purchase all their rice and wheat at PDS prices (*Ref + PDS scenario*). In this case, a slightly higher emissions reduction (133 million tonnes) can be achieved with a much smaller financial burden on the low-income households (about 0.6% increase in their food budget). Similarly, when we allow substitution between meat with vegetable protein (*Ref + FlexDiet*), emissions can be reduced further (149 million tonne CO2e) even with the PDS restriction with all but a few low-income groups (< 90 million people) staying within their food budget.

If households aim to achieve nutritional adequacy by minimizing overall deviations (by weight) from present diets (*DevMin* scenario), they would choose to significantly reduce foods from animal sources (because meats are very expensive, and milk products have low density,

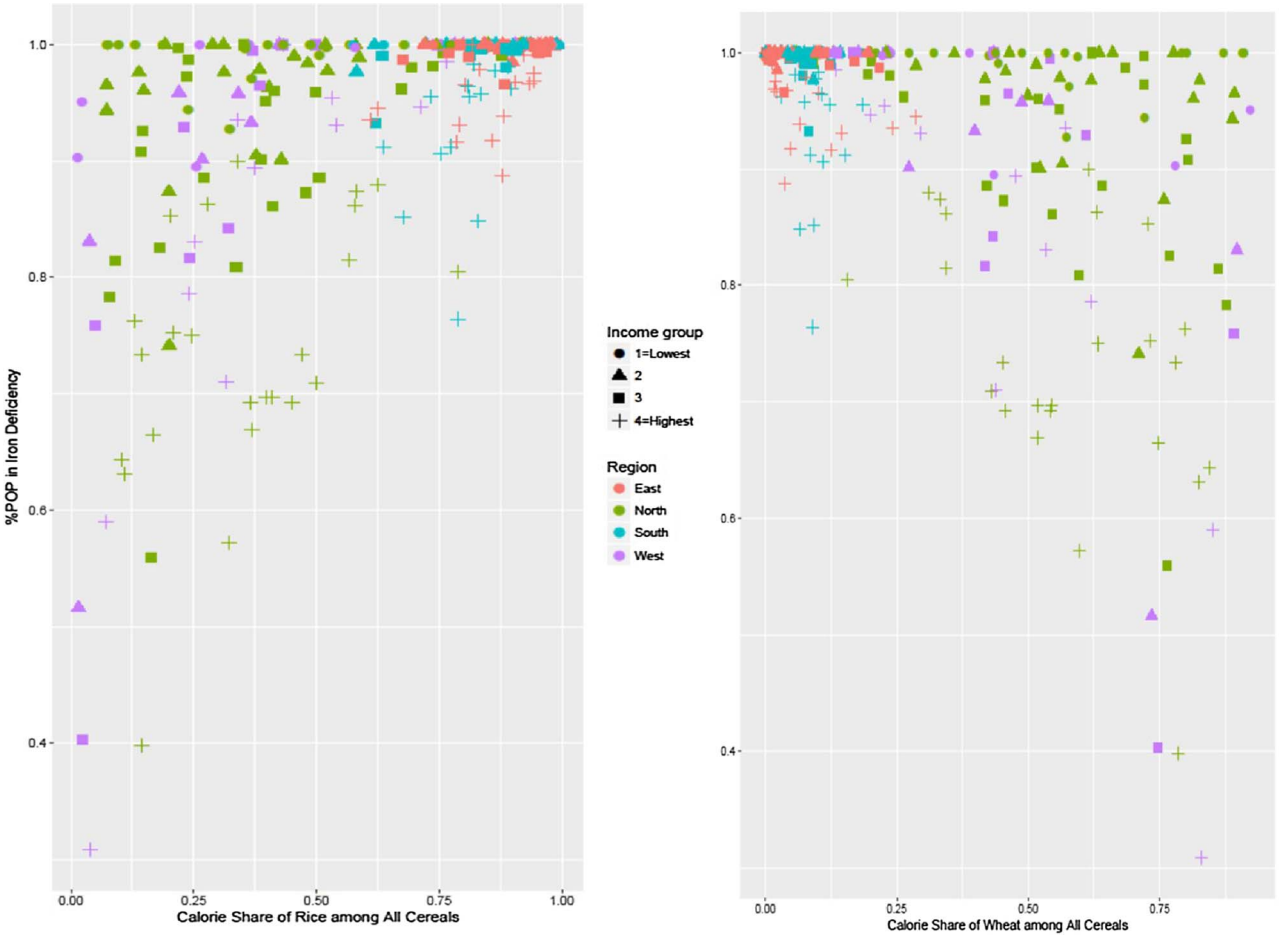

Fig. 4. Average share of population with iron deficiency against the average share of rice (left) and wheat (right) in total calories, by income group and region.

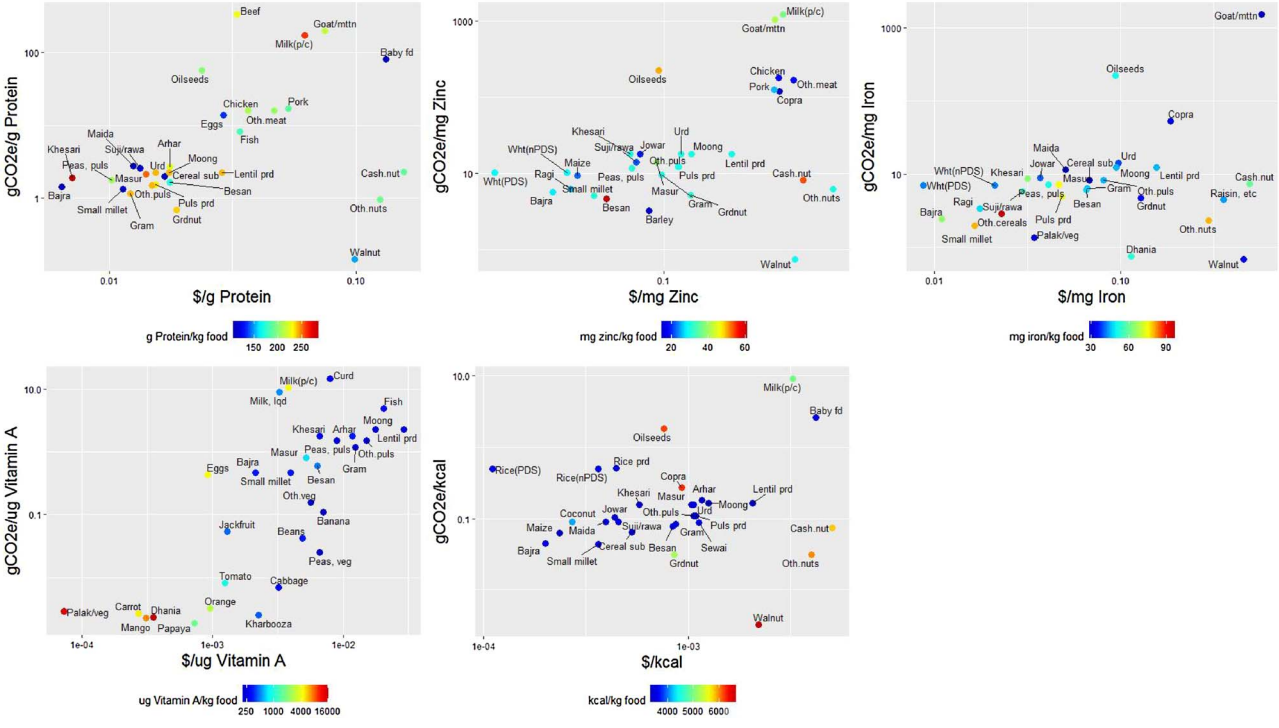

Fig. 5. Food item emissions and cost per nutrient. Color spectrum reflects nutrient share by weight. For each nutrient, top 30 food items (nutrient content by weight) shown. Both horizontal and vertical axes are in log scales. Bajra: pearl millet; ragi: finger millet; jowar: sorghum; Masur: red lentils; Arhar: split red gram (or split pigeon pea). Gram: bengal gram; khesari: lathyrus sativus (For interpretation of the references to color in the text, the reader is referred to the web version of this article.).

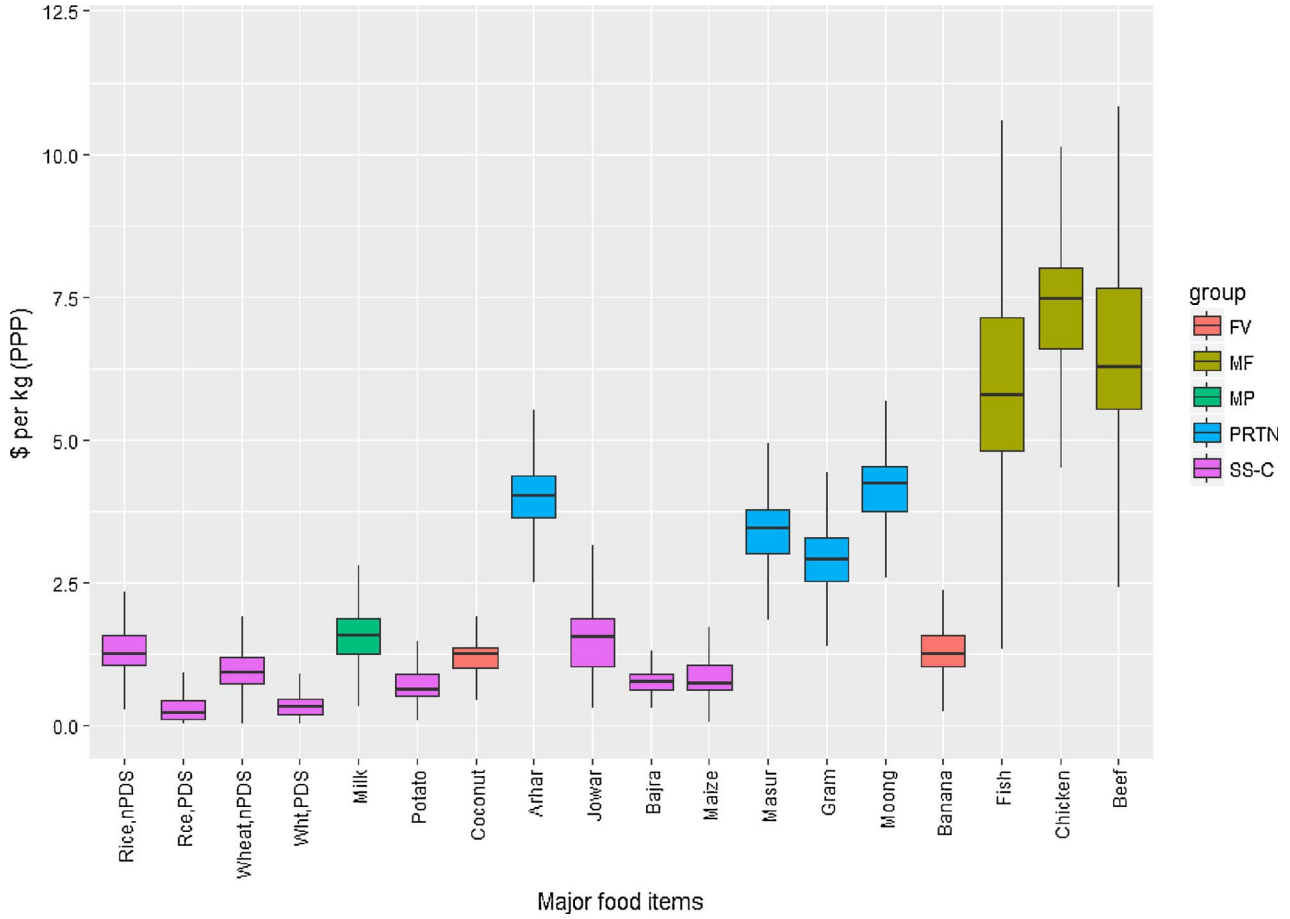

Fig. 6. Average per unit values paid by households for major food items. Data source: National Sample Survey of Consumption Expenditure, Round 68, 2011–12. Definitions: FV: fruit/vegetable, MF: meat/fish, MP: milk product, PRTN: non-meat protein source, SS-C: starch source; PDS: public distribution system (nPDS: not PDS); Bajra: pearl millet; jowar: sorghum; Masur: red lentils; Arhar: split red gram (or split pigeon pea). Gram: bengal gram; moong: green gram.

per nutrient) and consume more of other nutrient dense foods. The result is an even stronger case of a win-win for cost and emissions, because even the below-poverty households can meet their nutritional allowances within their budgets and lower emissions. However, it is not clear that this dietary shift would be more acceptable than the preferred diets from other scenarios.

These reductions are achieved mainly through moving away from rice to wheat, maize, bajra, and ragi; and from beef and eggs to chicken and legumes. Cereal calorie shares from rice and wheat shift from 56% and 34% in the baseline to 6% and 41% respectively in the *Reference* scenario (Fig. 8). The extent of this shift is highest in the *Reference*, since the objective is to minimize emissions and rice is emissions-intensive, and lowest in the *DevMin* scenarios, where the objective is to minimize deviations from present consumption. The obvious concern is whether such dietary shifts would be acceptable. That households do not eat better (nutrition-wise) even though many could do so within their food budgets (as reflected in the results of the *Reference* case) and save costs in some cases (as reflected in the *MinCost* scenario), shows that taste or other preferences dominate cost in decision-making.

5.2.2. Trade-off between cost and emissions

Achieving the cheapest possible diets or the lowest possible emissions while meeting nutritional requirements does involve trade-offs. Minimizing emissions without the food budget constraint (*Ref + NoBudget* in Fig. 7) yields emission reductions of around 24% (compared to 19% at *Reference*), but with high cost increases, particularly for lower income groups. These reductions are achieved mostly by even larger shifts away from rice, particularly in the South and East, where rice is cheap but emissions-intensive.

When we minimize cost exclusively (*MinCost* in Fig. 7), most households in the three higher income groups can meet their nutritional requirements and lower their emissions below baseline levels. For a small number of the two lowest-income household groups that are non-vegetarian (mostly in the Western region), emissions increase by up to 50% from the baseline because beef is the cheapest way to satisfy the nutritional requirements and maintain their current levels of meat consumption.

5.3. Discussion and policy implications

We find that micronutrient deficiencies in India are more prevalent than calorie and protein deficiencies. In particular, 85% of the population are deficient in iron, 89% in Vitamin A, and over two-thirds in zinc. Deficiencies are systematically higher at lower income levels, in both urban and rural areas, with few exceptions. These numbers are qualitatively consistent with the closest available point of comparison – a survey conducted by the National Nutrition Monitoring Bureau (NNMB) of 86, 898 individuals in rural areas in 2012 (National Nutrition Monitoring Bureau, 2012). Though the survey reports different metrics, they found intake deficiencies for Vitamin A and iron to be far higher than calorie deficiencies. For example, they report that 75–86% of households reported less than 50% of the RDA for Vitamin A, 31–92% of adult women consumed less than 50% of their RDA for iron, and the proportion of women consuming less than 70% of the RDA for energy ranged from 4 to 49% (state-wise averages). However, the NNMB does not provide systematic counts of intake deficiencies, nor do they provide any statistics for urban areas.

That urban households have higher protein, iron and zinc

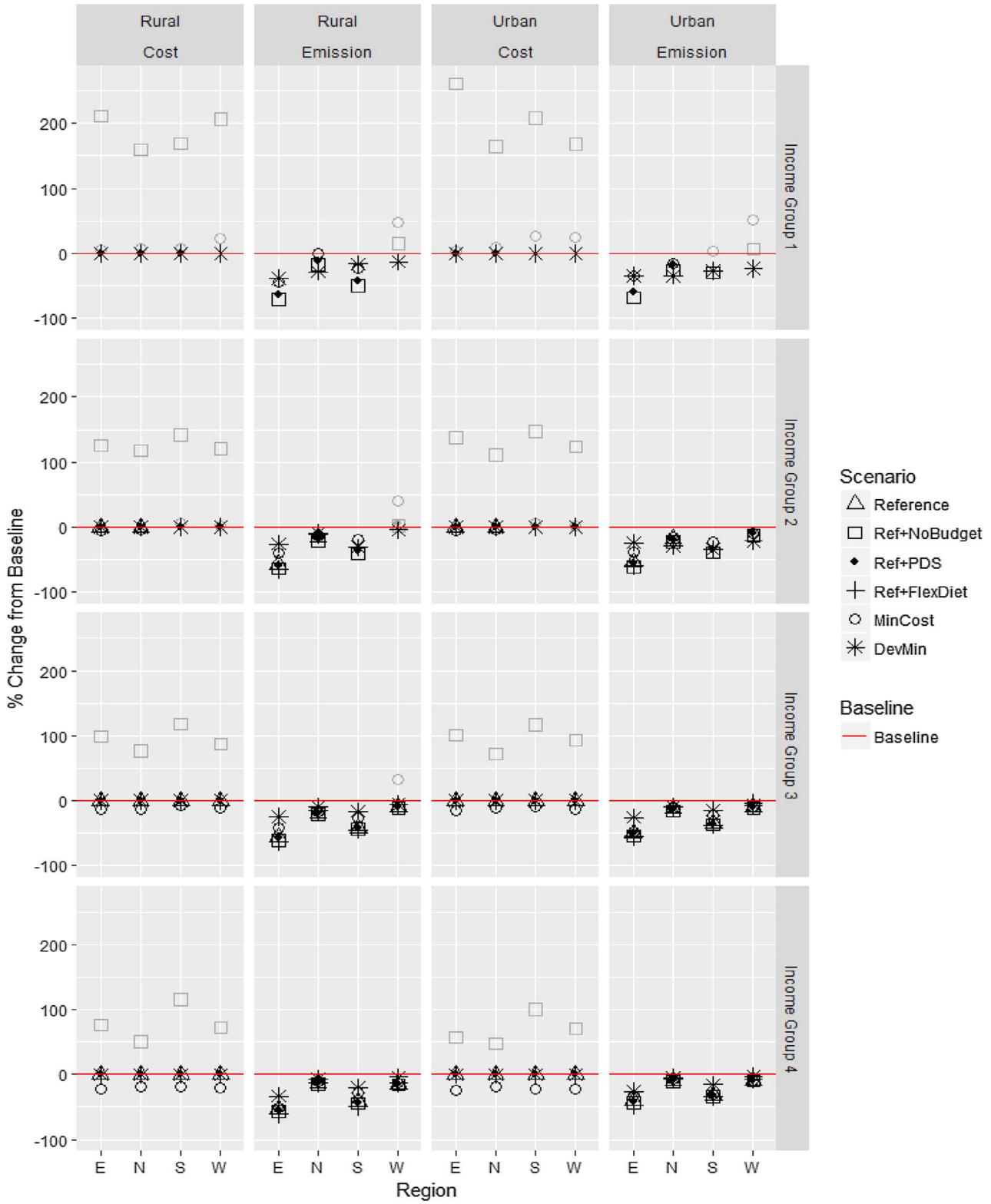

Fig. 7. Preferred diet scenario results, by region, income group and urban/rural. Percentage change in emissions and cost relative to those calculated for the survey (NSS 68, 2011–12). Scenarios below zero (dark tick marks) show 'win-win' cases. See Table 1 for scenario definitions.

deficiencies than their rural counterparts is an important finding, because the attention given to urban malnutrition has been limited and focused on obesity more than on intake deficiencies. Part of the reason for this result may be that rural households have higher calorie consumption, due to more labor-intensive livelihoods, which gives them additional micronutrients. Another contributing factor, though primarily in the West and North, is that rural households have more diversity in cereal consumption, with a larger share of coarse cereals (such as millets), which are more nutritious than both rice and wheat.

In a hypothetical exercise to examine the costs of dietary shifts that can alleviate these deficiencies, it appears that cost is not a hurdle to eating more nutritious diets, except for those below the poverty line.

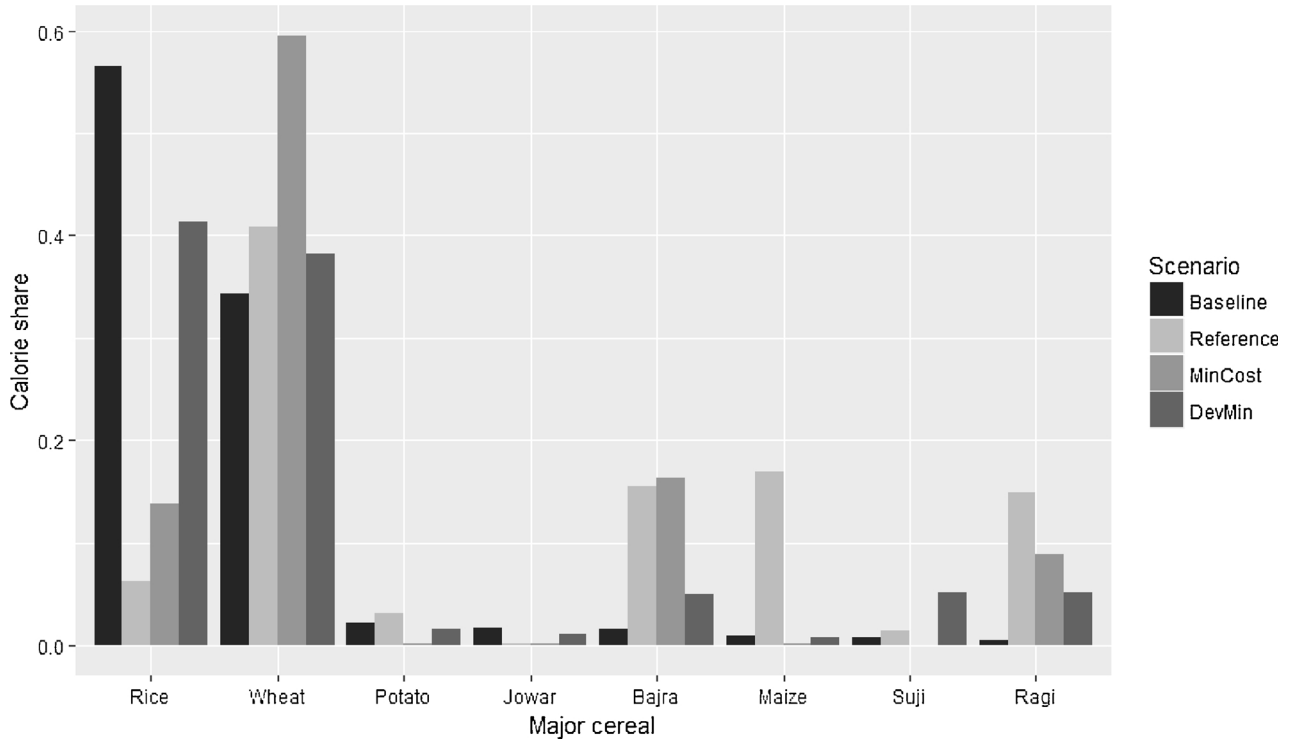

Fig. 8. Cereal calorie shares in the baseline and Reference preferred diet scenarios. bajra: pearl millet; jowar: sorghum; suji: semolina; ragi: finger millet. See Table 1 for scenario descriptions.

Overall, eating wheat and coarse cereals instead of rice, pulses instead of meat, and dark leafy vegetables and coconut would together alleviate deficiencies cost effectively. Even those in poverty could meet nutritional requirements within their budgets if they reduced milk product consumption. However, one caveat to this finding is that we don't consider calcium deficiency, which milk products are known to help alleviate.

There are limitations to this analysis, particularly arising from the use of NSS data. Nutrition from food eaten out is not known, and may not mirror home diets. Households that participate in mid-day meal and other such schemes may have better nutrition than what household expenditure may reflect. There is a need for more systematic and broad nutrition surveys with 24-h recall that can adopt advantages of both the NSS and current nutrition surveys. These results are based on current market conditions. If meat products, particularly non-ruminants, were substantially cheaper, it is possible that nutritional adequacy could be achieved more affordably than in our analysis, while still keeping emissions within current levels. In future work, different food subsidy policies and demand elasticities should be examined. Future work should also examine the production impacts of these dietary shifts, including the land use, price and supply chain impacts, to ascertain whether production scaling and availability of alternative foods, such as millets and pulses, is feasible across the country. Future studies should also examine whether these findings hold for other micronutrients, such as folate, calcium and Vitamin B12.

An additional limitation is lack of knowledge on how bioavailability of different nutrients alters intake requirements. Bioavailability varies with health status, processing techniques, which foods are eaten in combination (the food matrix), and other factors. The India-specific RDA values account for nutrient requirements based on the habitual Indian diet, but bioavailability is likely to vary substantially with other individual- and household-level factors (Schlemmer et al., 2009; Hallberg et al., 1989; Ma et al., 2007).

The climate co-benefits of eliminating micronutrient deficiencies and undernourishment are a new finding for India and offer opportunities to extend climate mitigation efforts in agriculture to demand side measures. In the least, this benefit provides yet another incentive to support ongoing efforts to encourage cereal diversity in food consumption. Should data become available, future studies should investigate the robustness of these findings to include indirect energy-related agricultural emissions.

There are other policy lessons suggested by this study. Food policy through the PDS appears to exacerbate nutrient deficiencies in two ways: by encouraging rice and wheat consumption over coarse cereals, and by enabling only a portion of households' rice and wheat consumption to be covered by the PDS. This gives poorer households less flexibility to diversify their diets. Extending the reach and scope of the PDS to increase the affordability and availability of coarse cereals and dark green vegetables, among other foods, would be important shifts. One major challenge in implementing these shifts is likely to be the acceptability of diversifying diets away from rice and towards coarse cereals. More research into understanding food preferences and their drivers, as well as the efficacy of public health and environmental awareness campaigns, would improve policy design.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2018.02.013.

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